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AN ASSESSMENT OF THE SOIL MOISTURE SENSORS FOR THE BUFFER/CONTAINER EXPERIMENTS

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ABSTRACT

In support of the buffer/container experiments to be conducted by AECL at the URL, three types of soil moisture content measuring sensor were assessed at the laboratory of the Civil Research Department, Ontario Hydro. Thermal needles were found to be more sensitive over the drier moisture range of the reference buffer whereas the Psychrometers were found to be more sensitive in the higher saturation level of the reference buffer. Because of the fragile construction of the Agwa sensors, they are not recommended for the buffer/container experiment No. 1.

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1.0 INTRODUCTION

In the proposed borehole emplacement scheme (TEC-2) of the Canadian nuclear fuel waste disposal vault concept/1/, the thermal performance of the buffer barrier will have a significant effect on the vault design. To assess the performance of the TEC-2 emplacement scheme, full scale buffer/container experiments will be conducted at the Underground Research Laboratory (URL). The layout of the planned experiments is shown in Figure 1. The predicted heater temperature versus time curves for the cases with the buffer remaining moist, and with the buffer becoming dry are plotted in Figure 2. The complete dry out of the buffer will result in a 20% increase in heater temperature. In the vault design, the canister's temperature has to be limited to a predetermined value. If the buffer is prone to drying and cracking due to thermal induced moisture migration, the spacing between canisters may have to be increased. Such an increase in the canister's spacing will result in a larger vault size that may render the disposal scheme uneconomical. Therefore, it is important to assess the thermal performance of the buffer under the vault environment.

In support of the buffer/container experiments to be conducted by AECL at the URL, the Civil Research Department, Ontario Hydro undertook a laboratory moisture content measuring sensor assessment program. The results of this study are presented in this report.

In situ moisture content is difficult to measure accurately by remote sensing. It has to be determined by correlation with other soil properties, such as electrical impedance, capacitance, soil suction/relative humidity or thermal conductivity. These correlations, however, are influenced by soil density, temperature, thermal gradients and pore water

chemistry. Therefore the types of sensors selected in this assessment program were calibrated in the reference buffer under appropriate hydraulic and thermal conditions.

2.0 CANDIDATE INSTRUMENTS

Based on a preliminary review of available sensors that could be used to determine moisture content, thermal needles, Agwa sensors, and psychrometers were selected for this assessment. Thermal needles measure the thermal conductivity of the surrounding soil, which is a function of its moisture content/2/. In this assessment program, thermal needles, 3 mm in diameter and 100 mm long, manufactured by Geotherm Inc were evaluated. The thermocouple-type psychrometers measure the relative humidity in soil that is directly related to its total suction potential. The total suction potential in a soil depends on both moisture content and the pore water chemistry. In this study, the Wescor PCT-55 type psychrometers were selected/3/. Agwa sensors are designed to measure the matric suction of the soil indirectly by measuring the heat dissipation rate through its porous ceramic block/4/. The matric suction in the porous block is in equilibrium with the matric suction of the surrounding soil/5/. The Agwa sensors used in this study were manufactured by Agwatronic Inc.

3.0 ASSESSMENT TEST RESULTS

In this assessment program, a reference buffer mix was statically compacted to a reference dry density of 1.68 Mg/m^3 at different moisture contents in 110 mm diameter by 300 mm long CPVC tubes. The sample tubes were moisture sealed at both ends. The temperature along the soil columns was monitored by thermocouples. The moisture sensors to be assessed were installed through the wall of each tube. The specimens were subjected to 20, 60 and 80°c in steps. The moisture sensors were monitored at each target temperature. After the 80°c ambient temperature step, the samples were allowed to cool to room temperature.

For assessing the effects of a thermal gradient on the sensor readings, a heater was installed at one end of each sample tube in direct contact with the buffer sample (Figure 3) and the sample tubes were encased in fibreglass insulation sleeves. The heater end of the sample tube was insulated, while the other end of the sample tube was exposed to the room temperature. By maintaining the heater temperature at 60°c, an uniform thermal gradient of 0.12°c/mm along the length of the sample was achieved. During this test, the sensors were monitored once a day. Once the sensor readings stabilized, the tubes were cut open and buffer samples along the length of the sample tubes and immediately adjacent to the moisture sensors were obtained for moisture content determination. Thus for each type of sensor the correlation curves between the sensor readings, and the moisture content and the temperature of the candidate buffer were established.

Thermal Needle

During a thermal conductivity measurement, an electrical current is applied to the heating coil within the thermal needle which induces a temperature rise in the needle above the adjacent soil. By monitoring the rate of temperature raise in the needle, the thermal conductivity of the adjacent soil can be calculated. The electrical current required decreases with the increase in accuracy of the temperature sensor within the needle. Since a thermistor has a higher degree of accuracy than the Type T thermocouple, a thermal needle with a thermistor will require less electrical current, and will induce less disturbance to the thermal regime within the soil. It will provide a more accurate thermal conductivity measurement than a thermal needle with a Type T thermocouple. The thermal conductivity versus moisture content relationship of the reference buffer was determined by the stage drying method with a thermal needle containing a thermistor. The results plotted in Figure 4 show that the thermal needle is sensitive over the range of moisture content that is of interest to the buffer/container experiment. Based on this study, thermal needles with thermistors are recommended.

A fourth degree polynomial function was fitted through the data points (measured by the thermal needle with a thermistor) as shown in Figure 4. The equation for the best fit curve is:

$$k_t = -1.098\times10^{-5} \times (m/c)^4 + 5.24\times10^{-5} \times (m/c)^3 + 6.38\times10^{-3} \times (m/c)^2 - 5.75\times10^{-3} \times (m/c) + 0.713 \quad (1)$$

Where k_t is the thermal conductivity of the buffer in w/m/°C, and (m/c) is the moisture content of the buffer in percent by dry weight . This equation is valid for the range of moisture content from 0 to 22%.

To assess the temperature effect, three specimens compacted to a reference dry density of 1.68 Mg/m^3 were tested at control ambient temperatures of 20, 40, 60 and 80 °c. The initial moisture contents of the three specimens were 3, 7.9 and 19.8%. The results of these tests, plotted in Figure 5, indicate that for the reference buffer the ambient temperature has minor effect on the thermal conductivity versus moisture content relationship. Therefore, no temperature correction on the thermal conductivity readings is required. The effect of temperature gradient on the thermal conductivity versus moisture content relationship was also found to be negligible.

Agwa Sensor

The Agwa sensor readings versus moisture contents of the reference buffer at room temperature are plotted in Figure 6. This figure indicates that the Agwa sensor is not very sensitive over the moisture content range from 0 to about 14%. It is important to note that the correlations between sensor readings and moisture content are sensor dependent. The effects of ambient temperature and thermal gradient on the Agwa sensor reading are shown in Figure 7. This figure shows that Agwa sensor readings are affected by the ambient temperature and the thermal gradient. The sensor readings decrease with temperature and temperature gradients. At a higher temperature, the Agwa sensor gives an apparent higher moisture content value than the true value. The Agwa sensors with a porous unbaked ceramic block were some what fragile and cracks developed during installation and retrieval of the sensors.

Psychrometer

In Figure 8, the psychrometer readings versus moisture content of the reference buffer are plotted. No readings could be obtained for the psychrometers installed in the buffer with moisture contents at 12% and 15%. This indicates that the psychrometers may not be able to measure the moisture content of the buffer below 15%. The best fitted curve with a third degree polynomial function is also plotted in Figure 8. The equation for this best fitted curve is:

$$PR = 1.159 \times 10^{-1} \times (m/c)^2 - 6.3787 \times (m/c) + 94.352 \qquad (2)$$

Where PR is the psychrometer reading, and (m/c) is the moisture content in percent by dry weight. This equation is valid for the moisture content range from 17% to 28%.

In Figure 9, psychrometer readings versus ambient temperature of the buffer at 18% and 25% moisture contents are plotted. This figure indicates that psychrometer readings are a function of ambient temperature. When thermal gradient is applied normal to the long axis of the sensor, it has minimal effect on the psychrometer readings. The porous ceramic tips of psychrometers were fragile but with care they could be easily installed without causing damage to the sensing element.

4.0 LEAD WIRE PROTECTION AND SEALING

The objective of moisture proofing the lead wires of the sensors is to eliminate any moisture leakage from the buffer to the experimental room through the lead wires. In addition, the instrument cables require protection sheaths to avoid damage caused by in situ buffer compaction.

The following lead wire protection designs are proposed for the three instruments:

Thermal needle - Figure 10 shows the prototype of a thermal needle. Water proofing of the probe is provided by sealing the lead wires into the sensor by epoxy. The lead wires are protected from the mechanical impact during compaction of the buffer by the high strength teflon sheath on the cables. A 90 degree bend in the probe needle is provided for routing the lead wires from the buffer to the borehole wall. The performance of the mechanical protection arrangement was tested during the URL buffer compaction trial and was found satisfactory.

Agwa sensor - Figure 11 shows the prototype of an Agwa sensor. Water proofing of the lead wires is provided by RTV sealant (heat resistant sealant for moisture, Dow Corning 736) that isolates the pathway between the conductor and the PVC jacket. This sealing mechanism has been pressure tested under 1.4 MPa (200 psi) water pressure. The lead wires are protected by a 9.5 mm (3/8") synflex tubing and swagelok. Experience has shown that the ceramic block of Agwa sensor is quite delicate and may not survive the calibration and installation procedures.

Psychrometer - Figure 12 shows the prototype of a psychrometer. The moisture proofing and mechanical protection for this sensor are similar to that for the Agwa sensor. The sensor is embedded in the synflex tubing. The gap between the sensor and the synflex tubing is sealed off by the RTV sealant (heat resistant sealant, Dow Corning 736). A more compact method of sealing and encapsulating the psychrometer has been successfully used by the AECL/WNRE Laboratory.

5.0 CALIBRATION PROCEDURES AND DATA LOGGERS

Thermal needle - The calibration of each sensor will be conducted by the manufacturer. Each sensor will be calibrated in Ottawa sand at room temperature. The thermal needles can be excited and monitored with Thermal Property Analyzer 5000 unit supplied by Geotherm Inc (Figure 13). The thermal conductivity versus moisture content relationship

expressed in Equation (1) can be used to calculate the moisture content of the buffer for the buffer/container experiment No. 1.

Agwa sensor - Each sensor has to be calibrated in a compacted buffer at various moisture contents and temperature (Figure 14). The sensors can be excited and monitored with a Campbell Scientific CR21 data logger. This is a tedious and time consuming process. The porous ceramic blocks of Agwa sensors are very fragile and tend to break while retrieving them.

Psychrometer - Each psychrometer has to be calibrated against a standard NaCl solution at room temperature. The psychrometers can be excited and read with a Campbell Scientific CR7X data logger (Figure 15). The psychrometer reading versus moisture content relationship at different ambient temperature has to be developed for calculating the moisture content of the buffer in the buffer/container experiment No. 1.

6.0 SUMMARY OF PERFORMANCE

In the planned URL buffer/container experiments, the moisture content of the buffer has to be monitored over a wide range from a near dry (close to the heater) to a near saturated level (at the buffer-rock contact). So the above three types of moisture sensors were assessed for their suitability. Due to their fragile construction and requirements for individual calibration of each sensor in the reference buffer, the Agwa sensors are not recommended for the buffer/container experiment No. 1. The psychrometers are suitable for use near the buffer/rock interface to record the moisture changes at higher saturation level. Appropriate corrections for ambient temperature have to be applied for the psychrometers.

Thermal needles are more sensitive over the drier range of the reference buffer. They can be used near the buffer/container interface, and within the buffer mass to monitor the moisture migration in the buffer.

Both thermal needles and psychrometers should be installed with their long axis perpendicular to the thermal gradients in the buffer.

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Mr. Bob Watts of the Civil Research Department performed most of the assessment tests. Mr. Bob Dowdell provided valuable suggestions. The thermal needles were designed and supplied by Geotherm Inc. Their contributions are gratefully acknowledged.

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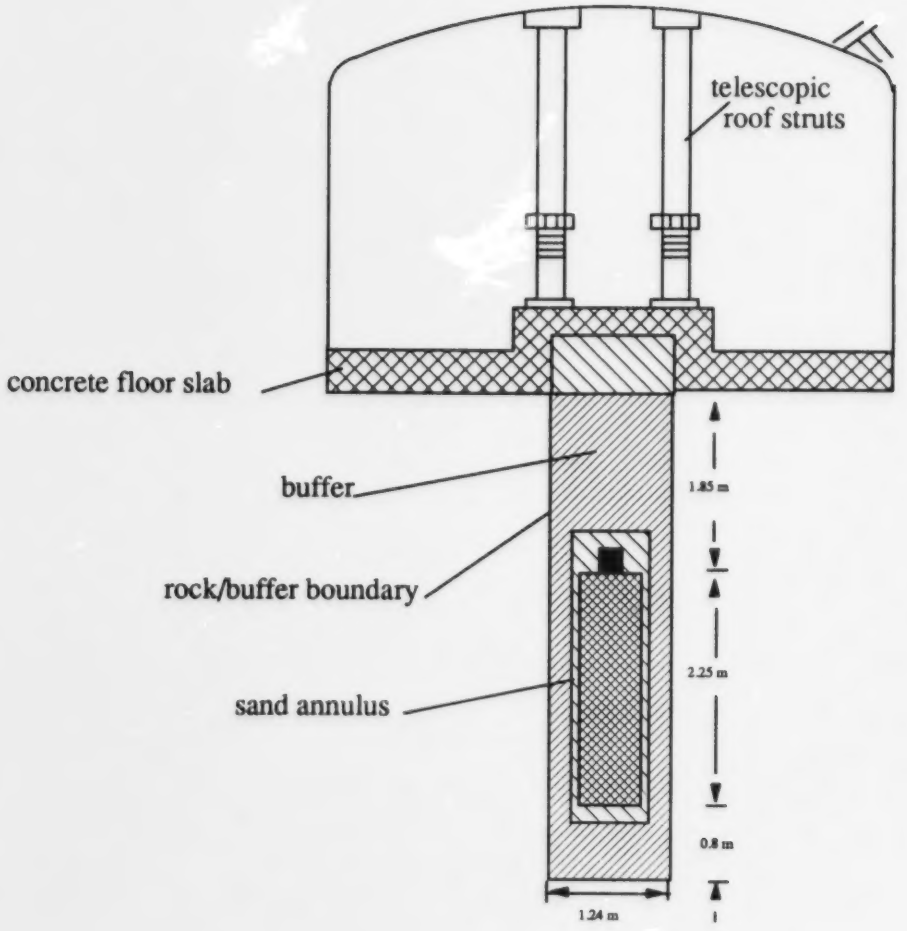


Figure 1 Layout of URL Buffer/Container Experiment.

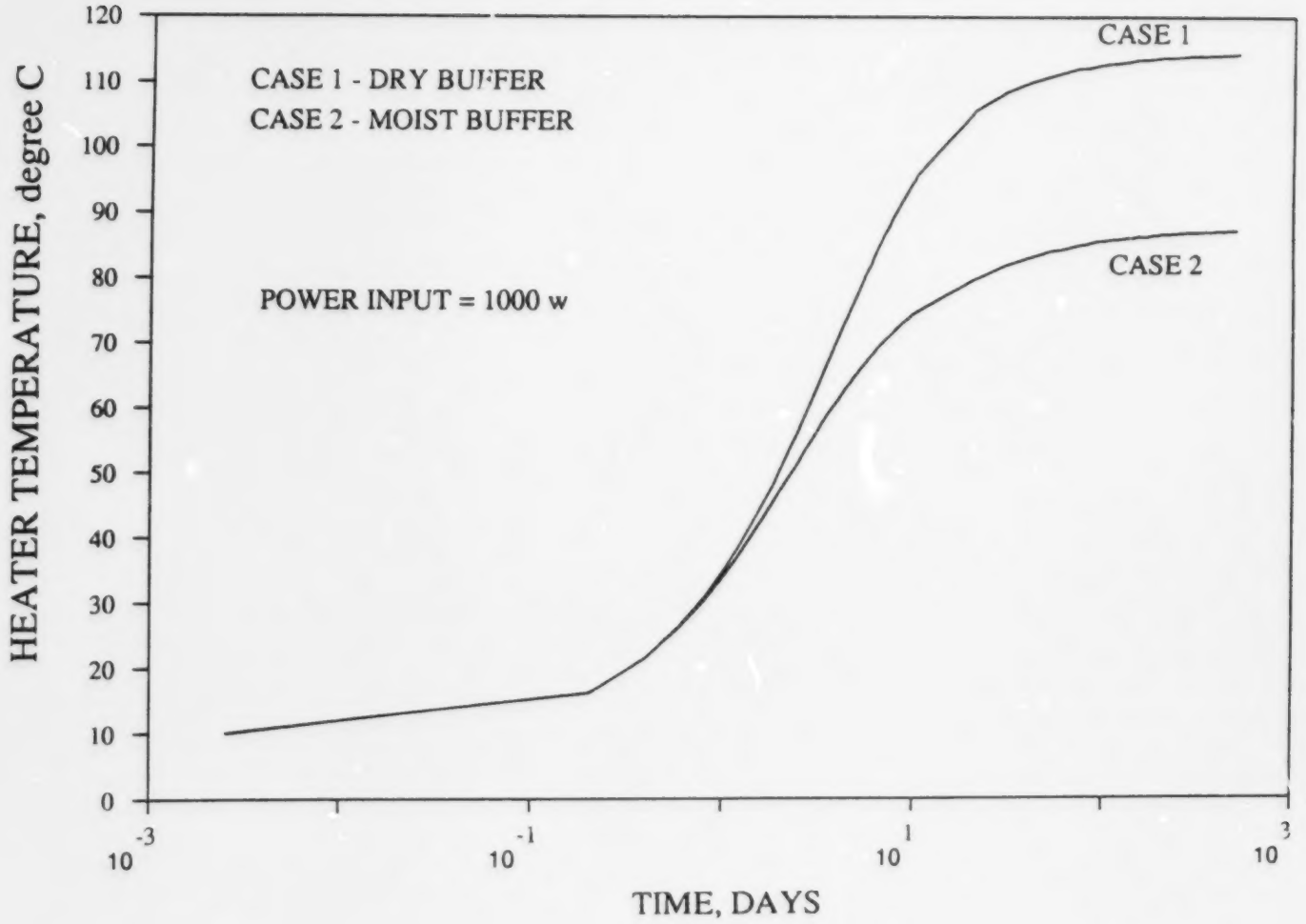


Figure 2 Predicted Temperature vs. Time Curves - Buffer/Container Experiment No. 1.

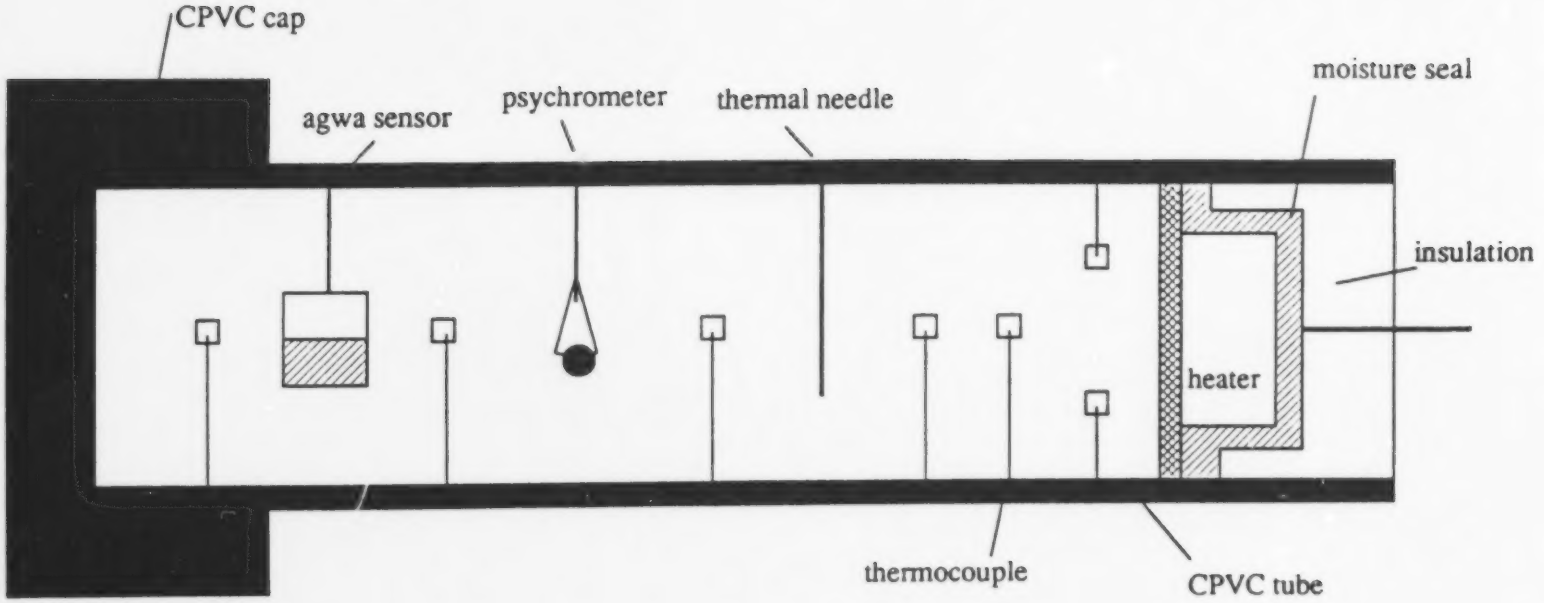


Figure 3 Moisture Sensor Calibration Setup.

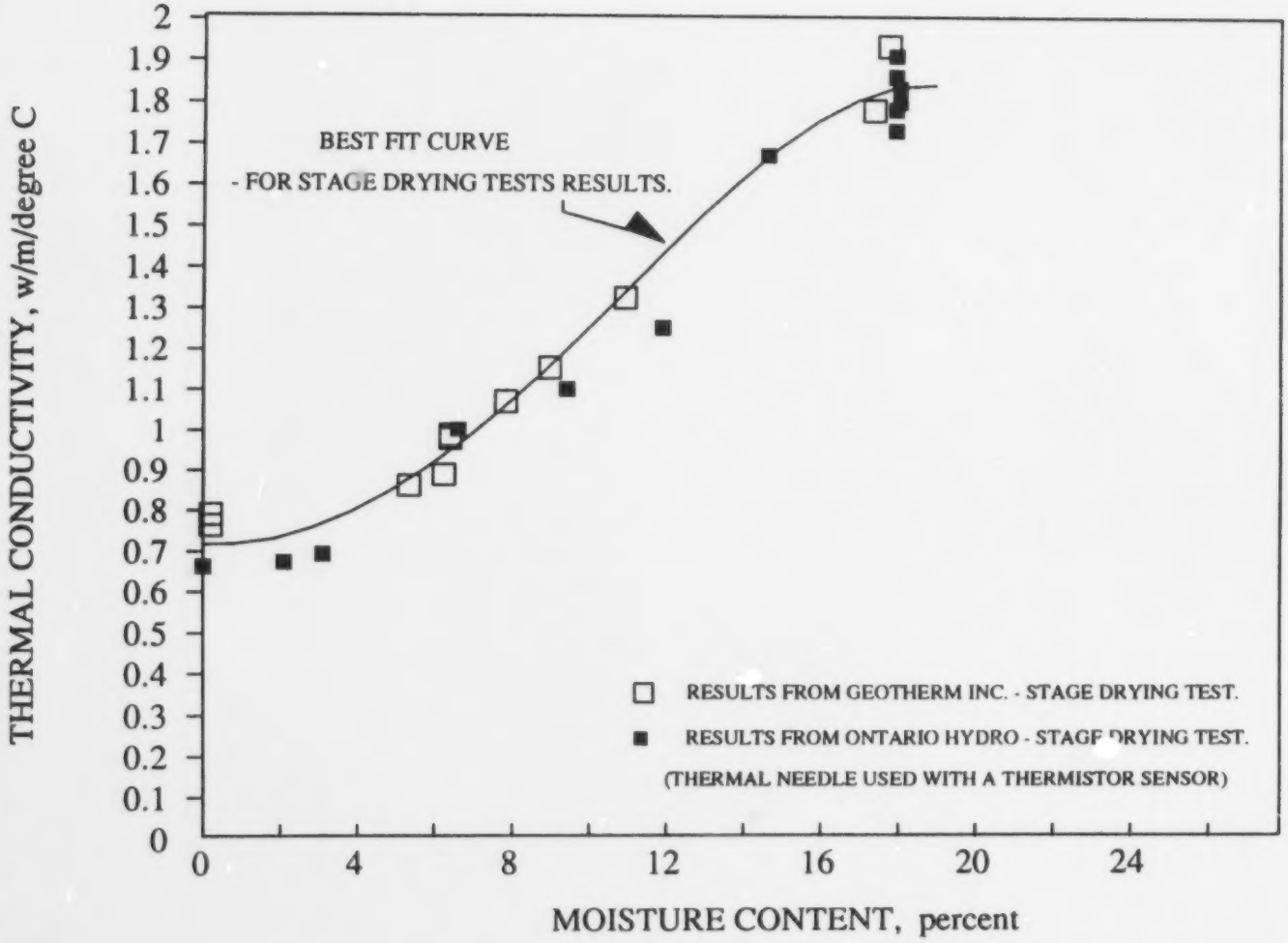


Figure 4 Thermal Conductivity vs. Moisture Content - Reference Buffer.

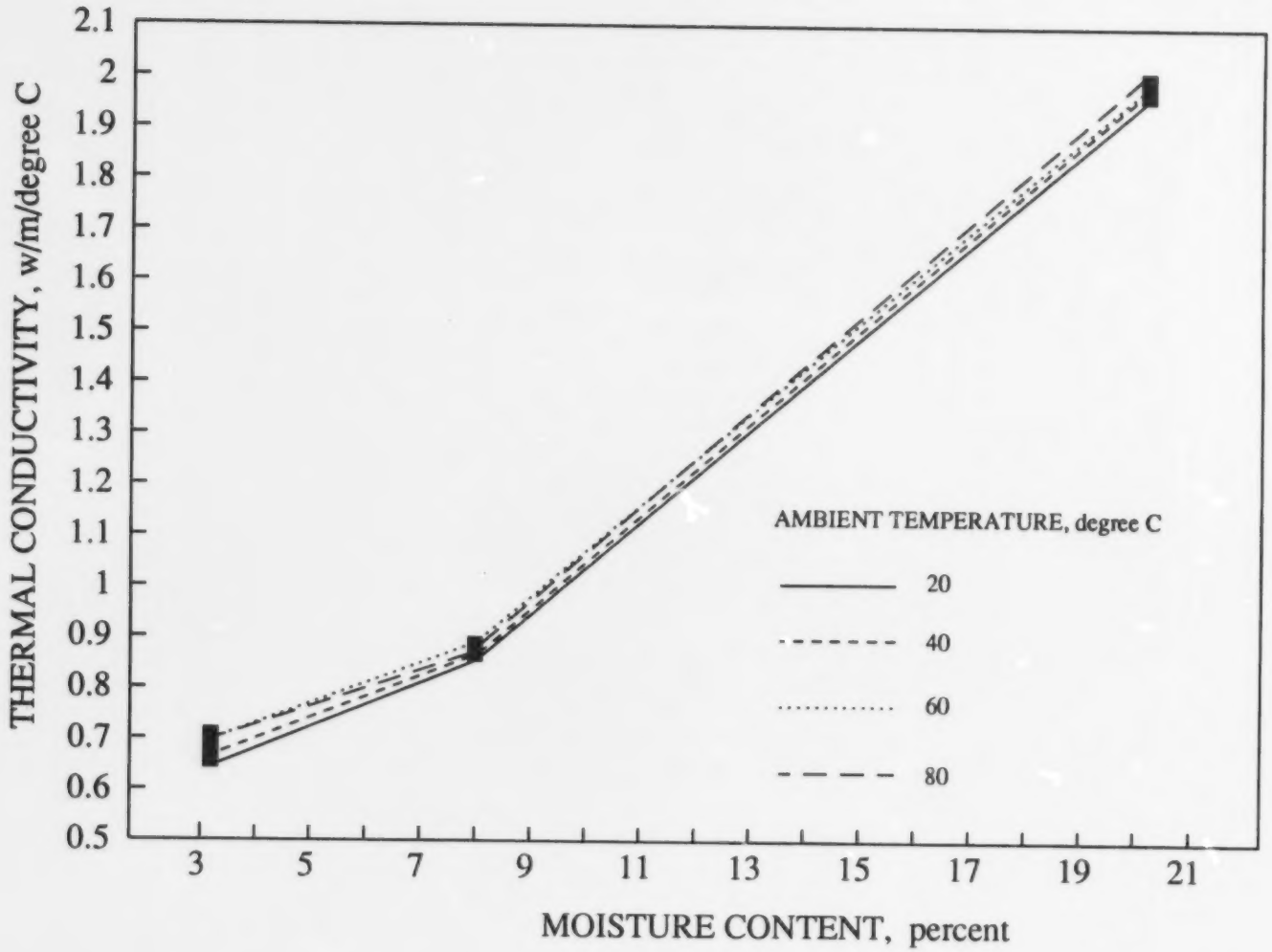


Figure 5 Effect of Ambient Temperature on the Thermal Conductivity of the Reference Buffer.

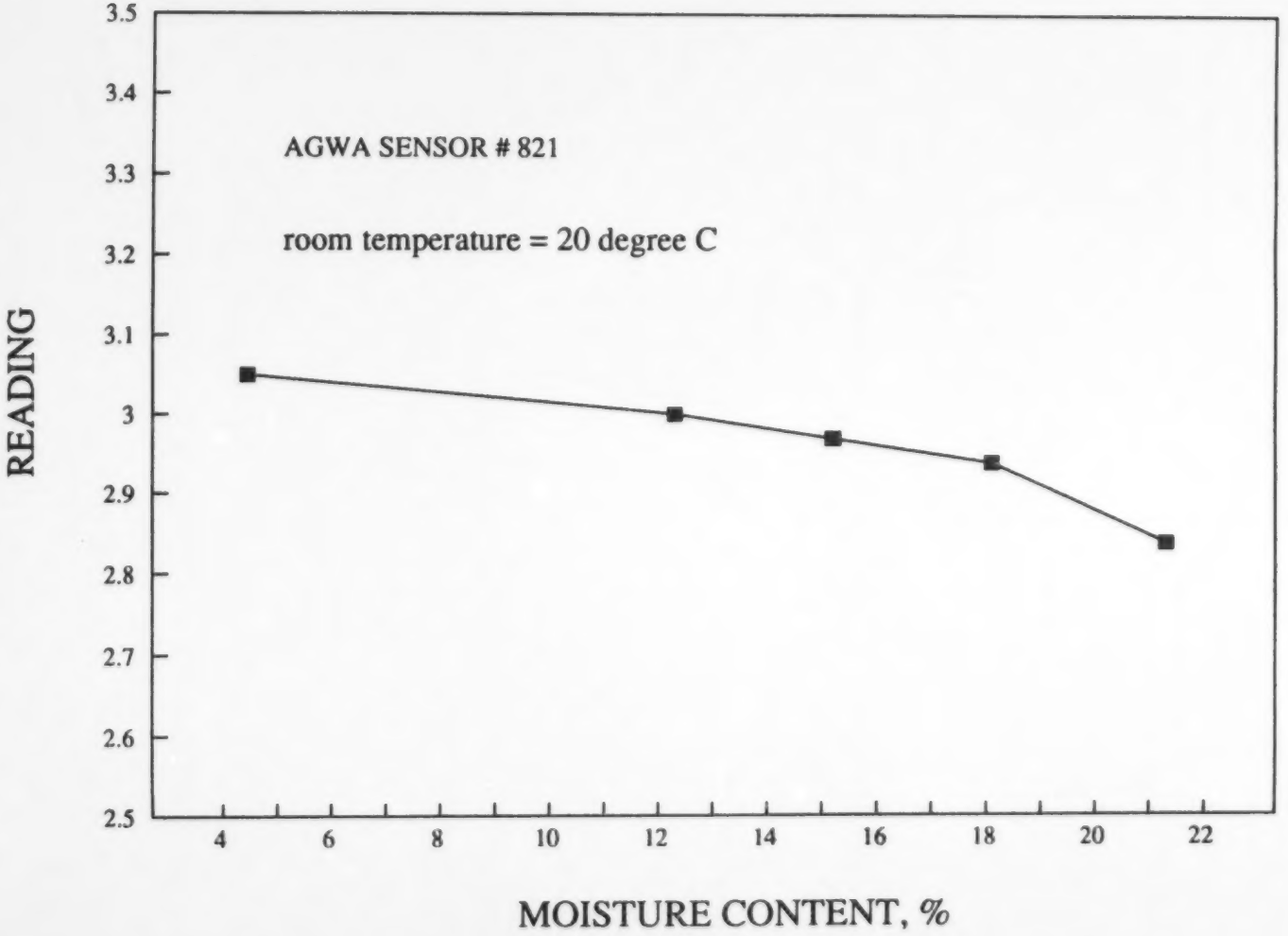


Figure 6 Agwa Sensor Readings vs. Moisture Content of the Reference Buffer.

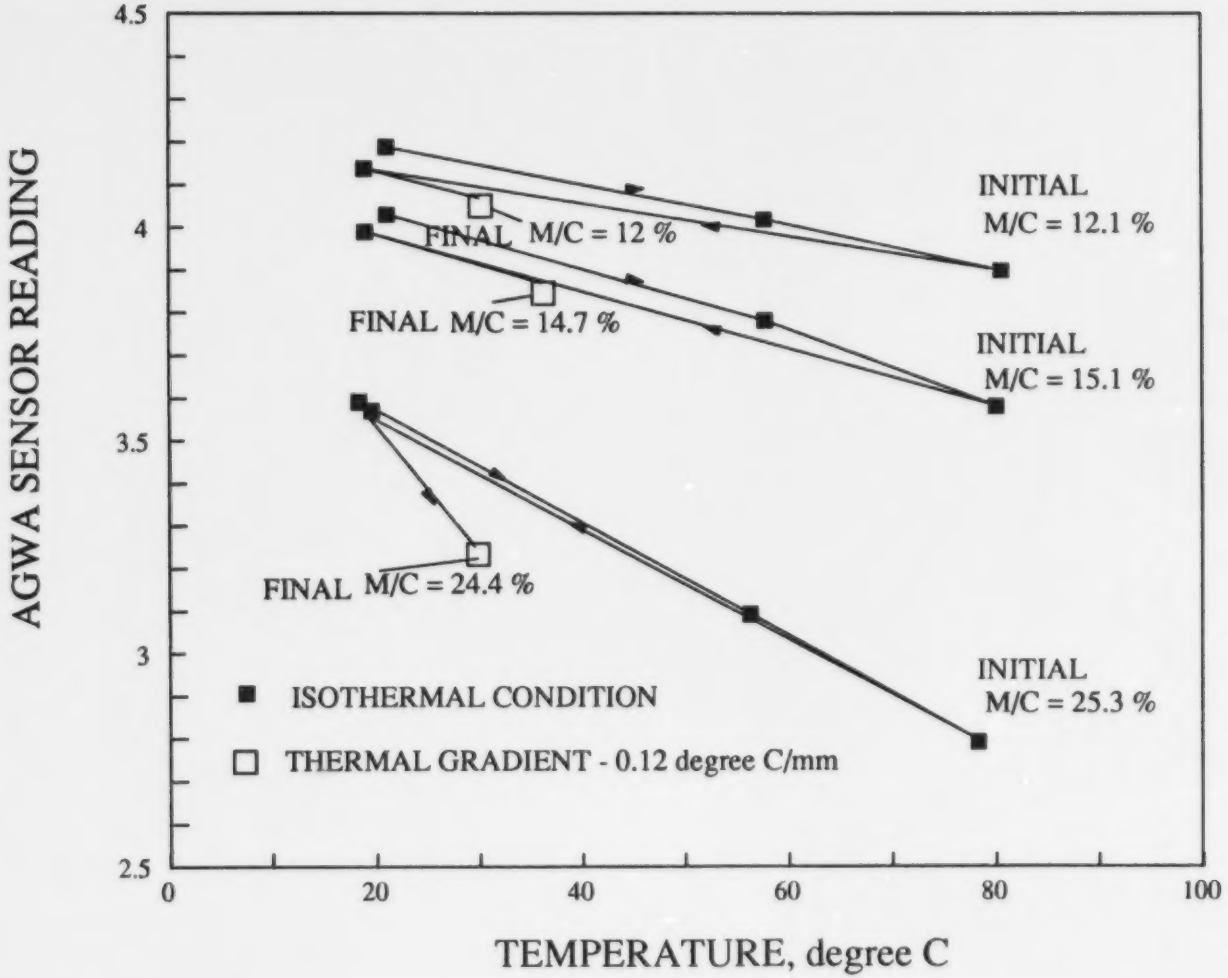


Figure 7 Agwa Sensor Reading vs. Temperature in Reference Buffer.

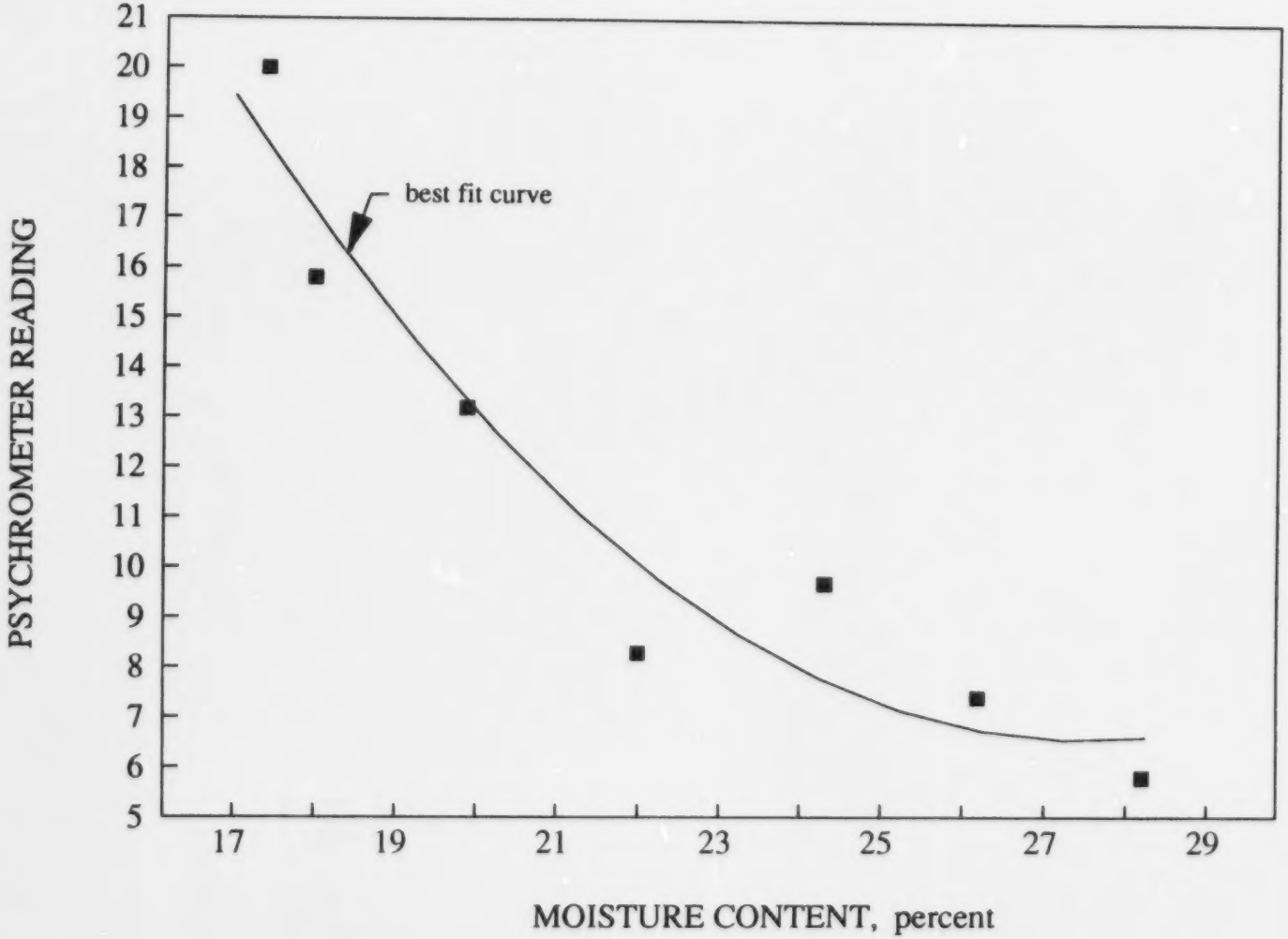


Figure 8 Psychrometer Reading vs. Moisture Content - Reference Buffer.

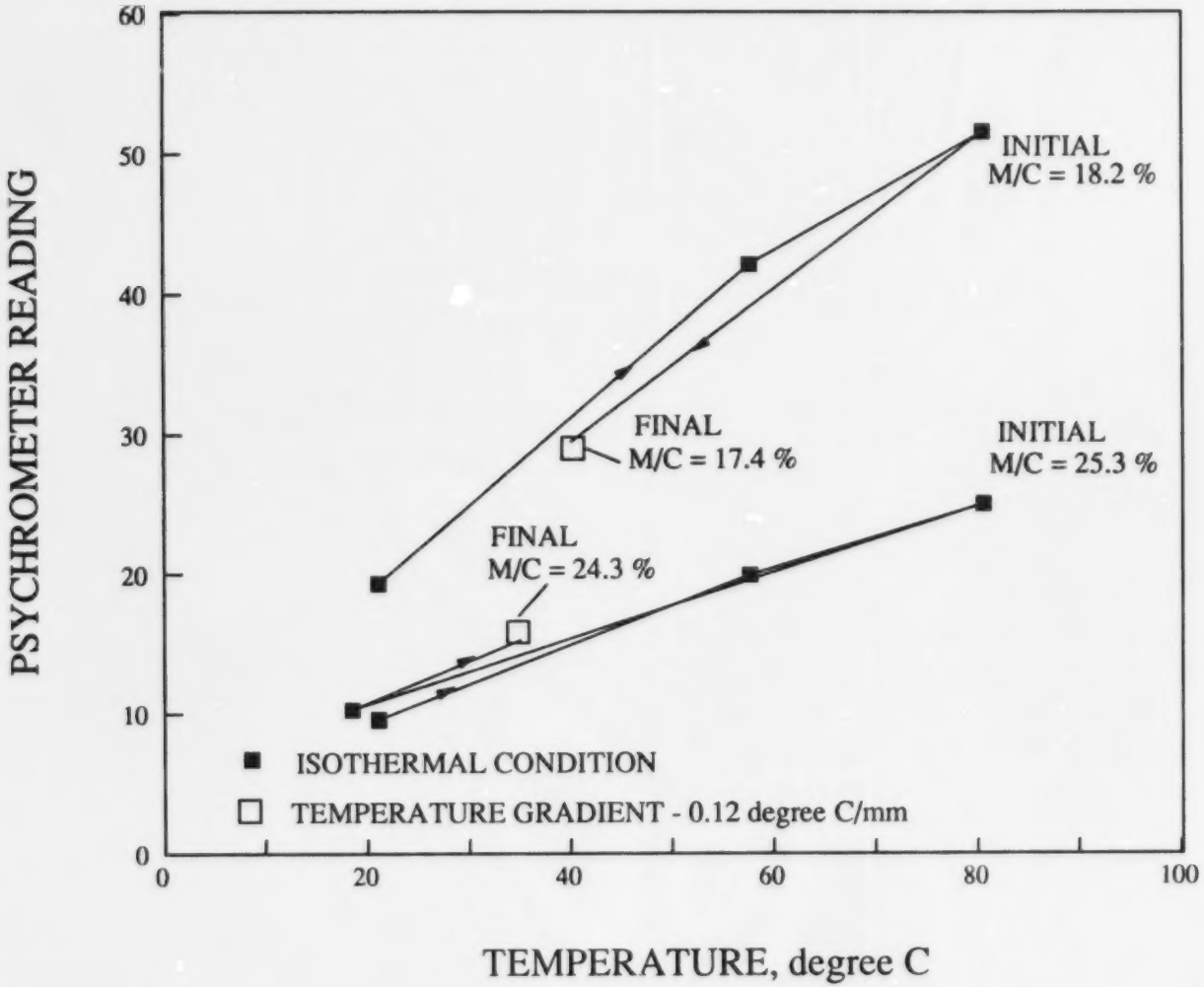


Figure 9 Psychrometer Readings vs. Temperature in Reference Buffer.

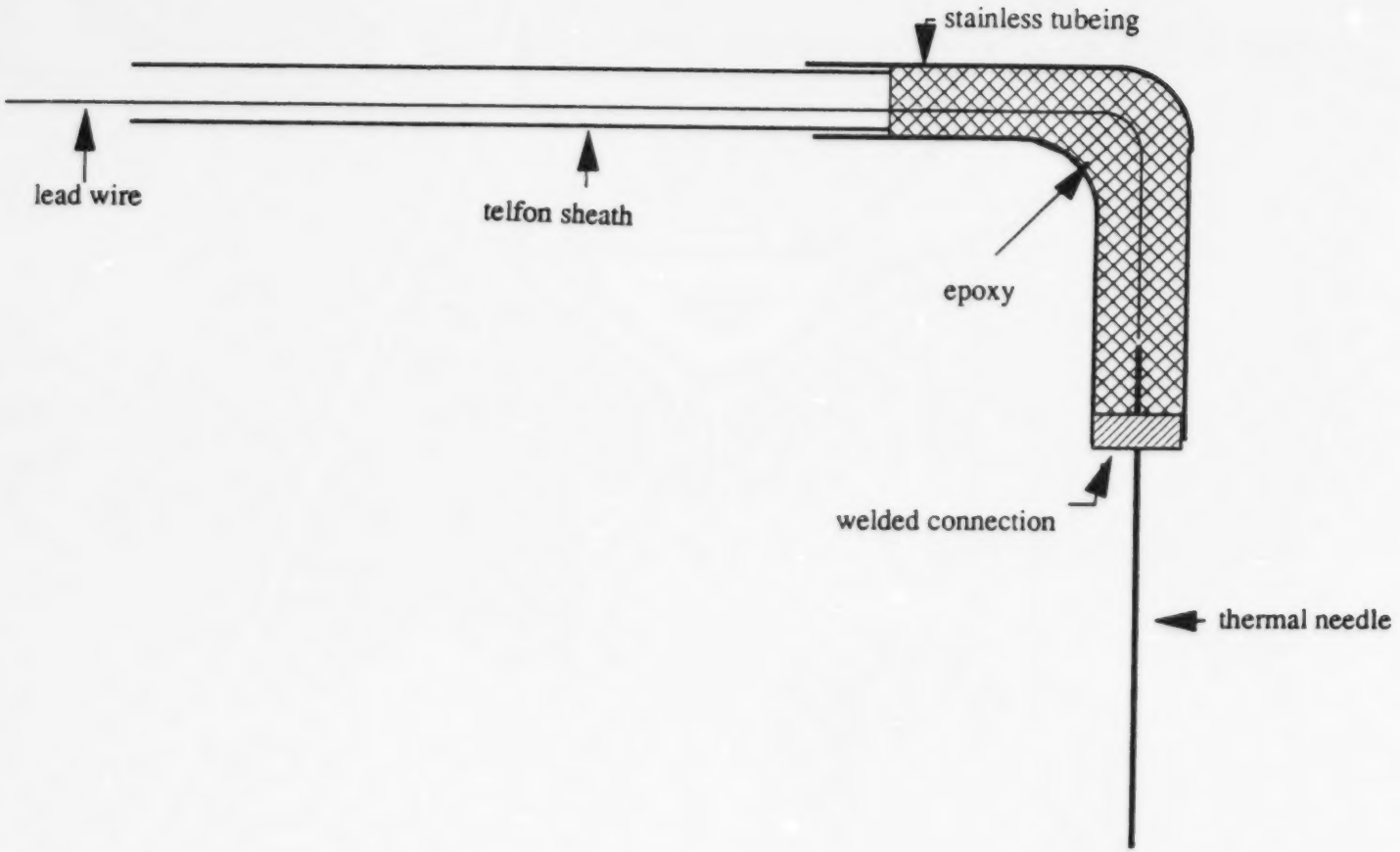


Figure 10 Prototype of the Thermal Needle.

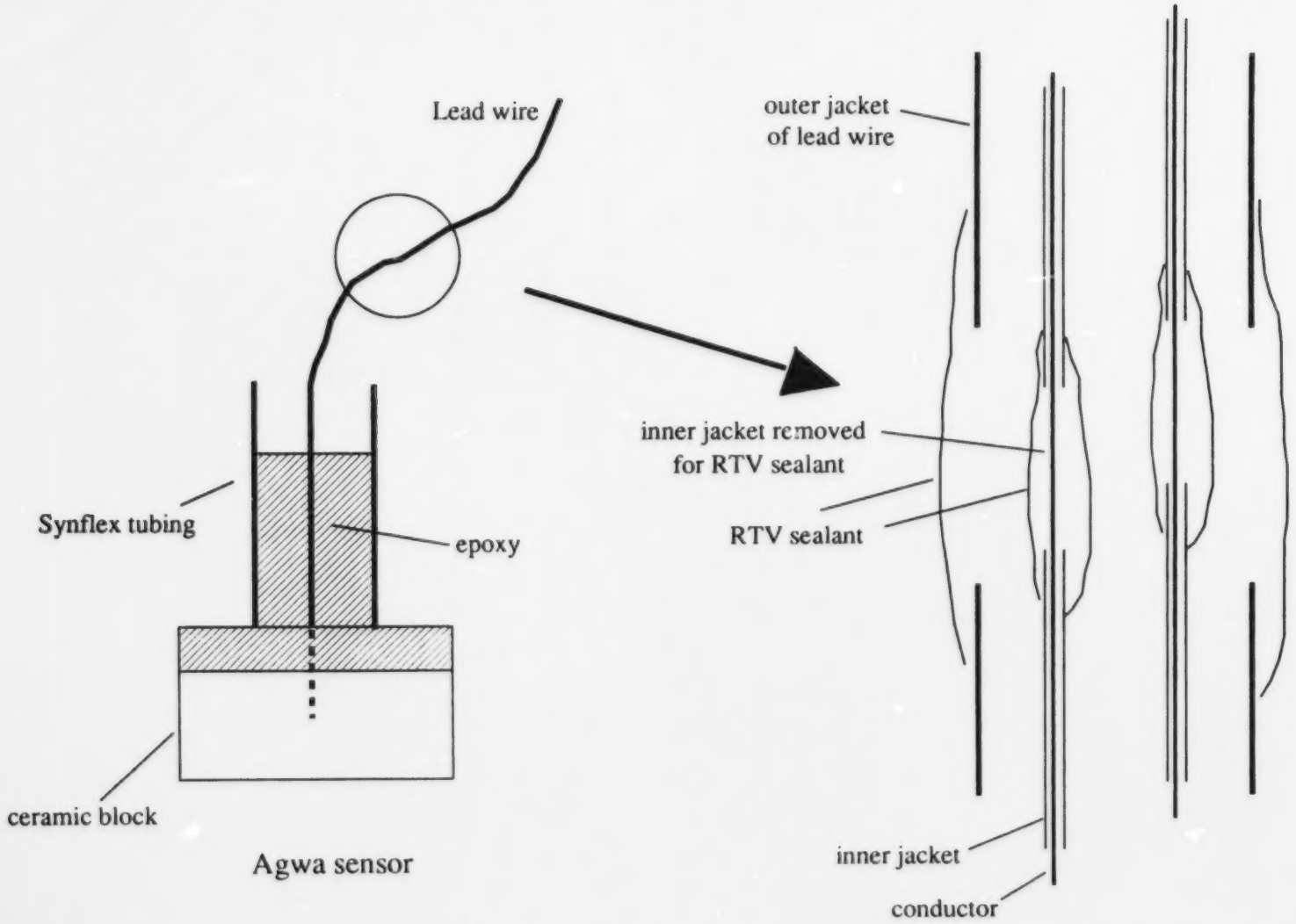
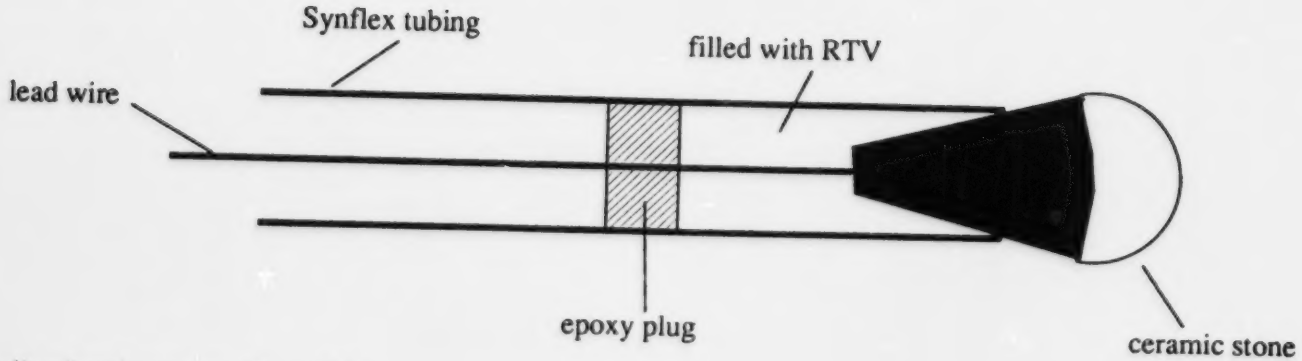


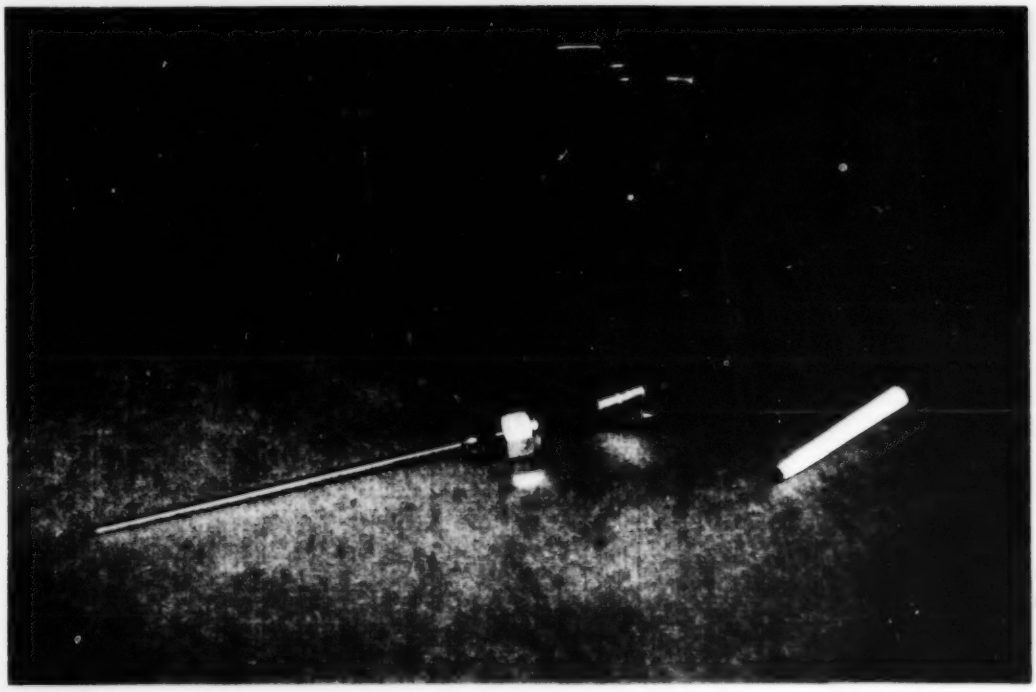
Figure 11 Prototype of Agwa Sensor.



Note: Details of moisture proofing of the lead wire refer to Figure 11

Psychrometer

Figure 12 Prototype of Psychrometer



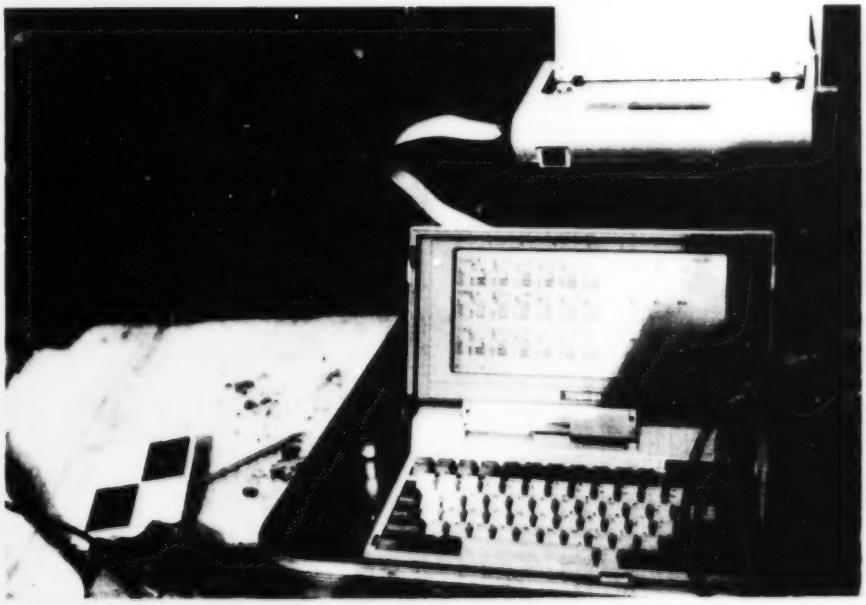


Figure 13 The Thermal Needle and The TPA 5000 Unit.

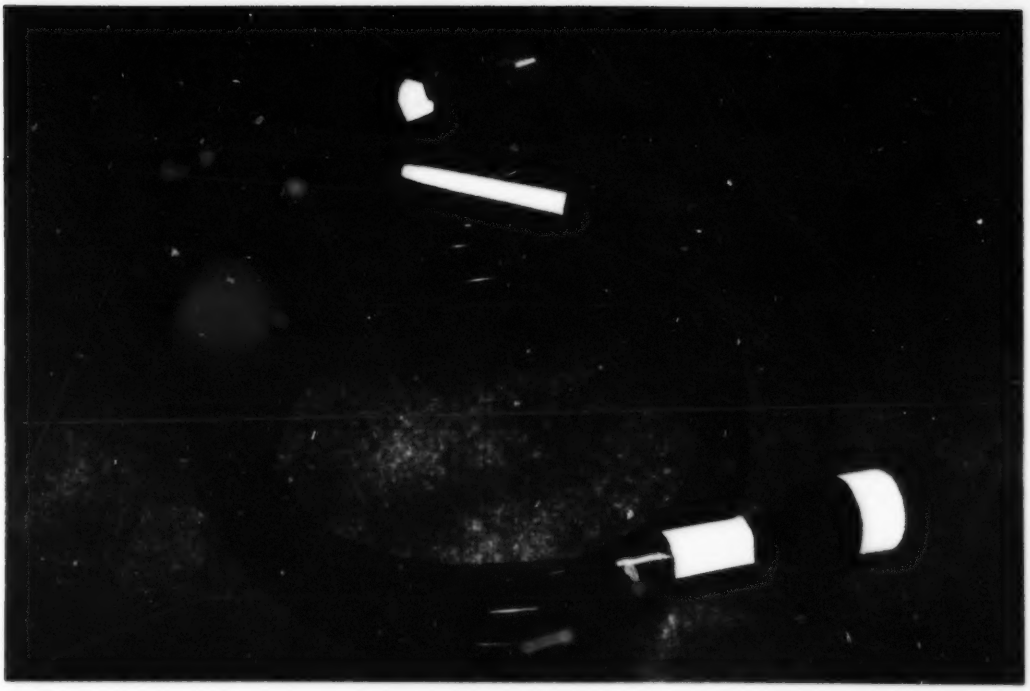


Figure 14 The Agwa Sensor and The Campbell Scientific CR21 Data Logger.

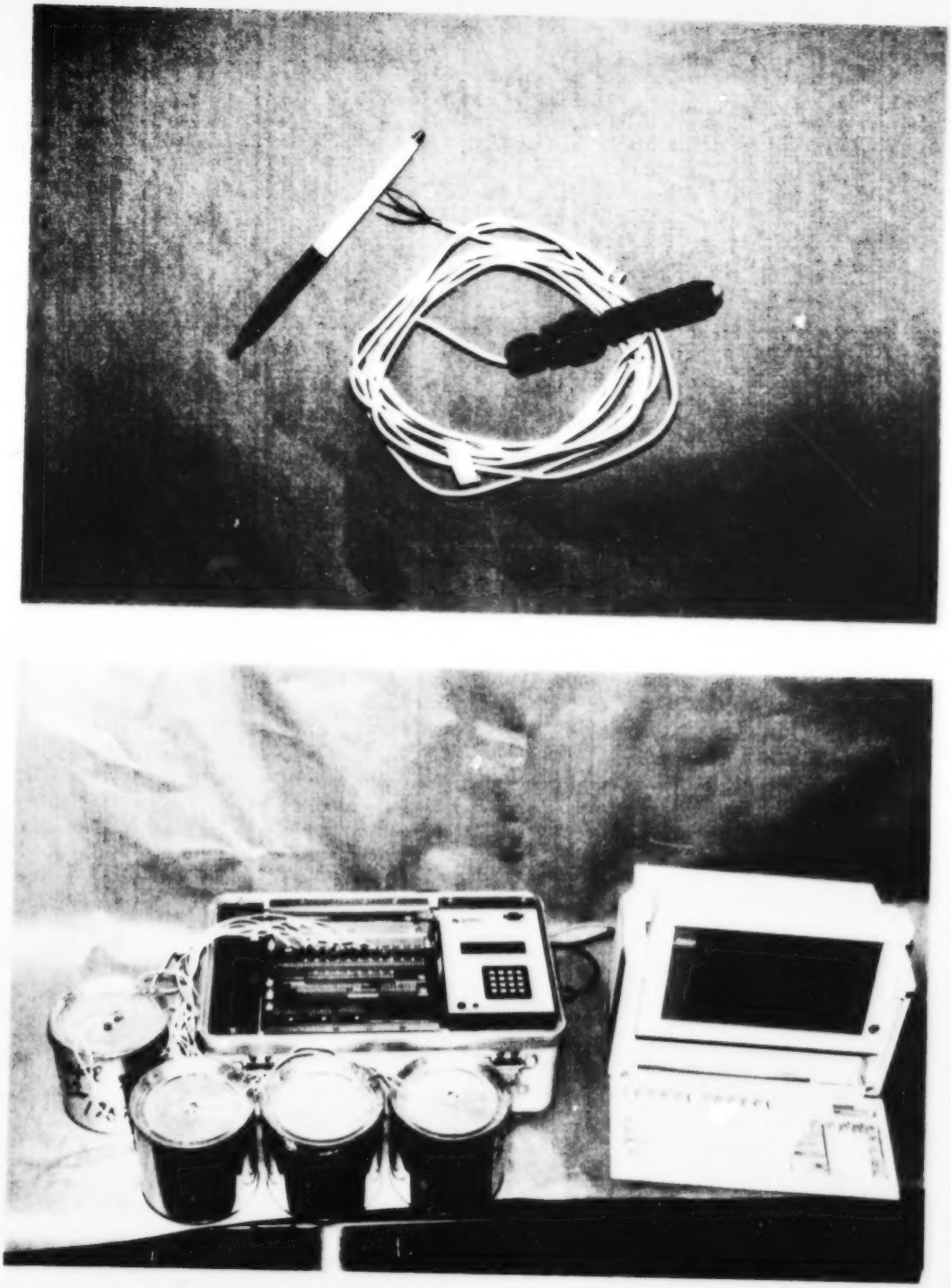


Figure 15 The Psychrometer and The Campbell Scientific CR7X Data Logger.